

The sensitivity of the Higgs boson branching ratios to the W boson width

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Abstract

The Higgs boson branching ratio into vector bosons is sensitive to the decay widths of those vector bosons because they are produced with at least one boson significantly off-shell. $\Gamma(H \rightarrow VV)$ is approximately proportional to the product of the Higgs boson coupling and the vector boson width. Γ_Z is well measured, but Γ_W gives an uncertainty on $\Gamma(H \rightarrow WW)$ which is not negligible. The ratio of branching ratios, $\text{BR}(H \rightarrow WW)/\text{BR}(H \rightarrow ZZ)$ measured by a combination of ATLAS and CMS at LHC is used herein to extract a width for the W boson of $\Gamma_W = 1.8^{+0.4}_{-0.3}$ GeV by assuming Standard Model couplings of the Higgs bosons. This dependence of the branching ratio on Γ_W is not discussed in most Higgs boson coupling analyses.

This is not the work of, nor endorsed by, the ATLAS or CMS collaborations.

1 Introduction

The Higgs boson discovered at LHC[1, 2] has been the subject of combined mass[3] and couplings[4] analyses by the ATLAS and CMS collaborations. The couplings analysis uses the so-called κ framework of the LHC Higgs cross-section working group[5, 6], and relies upon the cross-section and branching ratio calculations contained therein. This includes the properties of the vector bosons, W and Z , for which the masses reported in the RPP[7], are used to extract pole masses of $m_Z = 91.15349$ GeV and $m_W = 80.36951$ GeV in Ref.[6]. In addition, and especially relevant for this note, the vector boson widths are calculated from their masses and assuming the Standard Model(SM), to be $\Gamma_Z = 2495.81$ MeV and $\Gamma_W = 2088.56$ MeV.

The use of the theoretically expected W boson width is not discussed in Ref. [6], it is merely stated. It is not obvious that this is the best motivated assumption when looking for beyond the Standard Model (SM) effects in Higgs boson properties. The primary purpose of this document is to highlight that assumption.

The widths of the Z and W bosons have also been measured experimentally. The Z boson width is measured via the scan of the Z resonance at LEP[8] to be 2495.2 ± 2.3 MeV. The W boson width has been measured using mass reconstruction at LEP 2 [9] and with better precision using the transverse mass distribution at the Tevatron [10]. These different approaches agree well and are combined in the RPP[7] to give $\Gamma_W = 2085 \pm 42$ MeV, an error a factor twenty times larger than that for the Z . In consequence, effects due to the vector boson width uncertainties are dominated by those from the W boson.

The Higgs boson partial widths and branching ratios are not experimentally accessible at the LHC, where only products of production and decay can be studied. However, the ratio of the branching ratios to WW and ZZ , is measurable, and it is presented in Ref. [4]. The measured value of $\text{BR}^{WW}/\text{BR}^{ZZ}$ is $6.8^{+1.7}_{-1.3}$. It is also accurately calculable, using just m_H and the masses and widths of the W , Z and H bosons. The SM value given in Ref. [6] is 8.09

This ratio is not the only test of the $H \rightarrow WW$ width which could be made. Most obviously the measured rate into diphotons could be included in the analysis. However, further assumptions about the interaction strengths of all particles entering the decay loop would be needed, and there could even be unknown particles. The analysis using the vector bosons alone is easier to justify.

2 Analysis of the widths

The full calculation of the Higgs boson partial widths in the SM is rather complex. However, the results are tabulated in Ref. [6], and the approach taken here is to use a leading-order approximation [11], and then scale its results to those in Ref. [6] for the nominal input parameters. This captures the dependence on the W boson width to a very good approximation. The calculation is reproduced below.

$$\Gamma(H \rightarrow V^*V^*) = \frac{1}{\pi^2} \int_0^{M_H^2} \frac{dq_1^2 M_V \Gamma_V}{(q_1^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \int_0^{(M_H - q_1)^2} \frac{dq_2^2 M_V \Gamma_V}{(q_2^2 - M_V^2)^2 + M_V^2 \Gamma_V^2} \Gamma_0. \quad (1)$$

In this formula Γ_0 is

$$\Gamma_0 = \delta'_V \frac{G_F M_H^3}{16\sqrt{2}\pi} \sqrt{\lambda(q_1^2, q_2^2, M_H^2)} \left(\lambda(q_1^2, q_2^2, M_H^2) + \frac{12q_1^2 q_2^2}{M_H^4} \right) \quad (2)$$

where $\lambda(x, y, z) = (1 - x/z - y/z)^2 - 4xy/z^2$ and δ'_V has different values depending upon the vector boson: $\delta'_W = 2$ and $\delta'_Z = 1$ [11]. By performing the integration the partial width can be found. This calculation assumes the SM coupling strengths to the W and Z boson.

Figure 1 shows the density of the partial width of the Higgs to vector boson pairs in the (q_1, q_2) plane. It is shown for Higgs boson masses of 100 and 200 GeV (bottom row) to demonstrate the impact on the phase space of the Higgs boson mass. For the 200 GeV case the whole resonant structure is observed, and the factor Γ_V in equation 1 will largely cancel in the integration. For lower masses only one, or perhaps no, clear resonant structures dominate and there will be one or two factors of Γ_V in the solution.

The numerical evaluation uses the parameters from the LHC Higgs cross-section working group as given in the introduction and was done using root [12]. To check the calculation it is first evaluated at $m_H = 126$ GeV because Ref. [6] provides partial widths at this mass. The values obtained are 0.941 MeV for WW and 0.119 MeV for ZZ . These are respectively 97% and 98% of the values from the reference, 0.974 MeV and 0.122 MeV. This 2-3% discrepancy with the full calculation shows that the higher order effects are not large.

Having tested the implementation, the partial widths are found at $m_H = 125.09$ GeV. They are $\Gamma(H \rightarrow WW) = 0.853$ MeV and $\Gamma(H \rightarrow ZZ) = 0.107$ MeV.

The ratio of the partial widths gives directly the ratio of the branching ratios, 7.99. This is about 1% lower than the 8.09 contained in Ref. [6] and the difference is assumed to come from the more complete calculation used in that document. The 2-3% changes in the WW

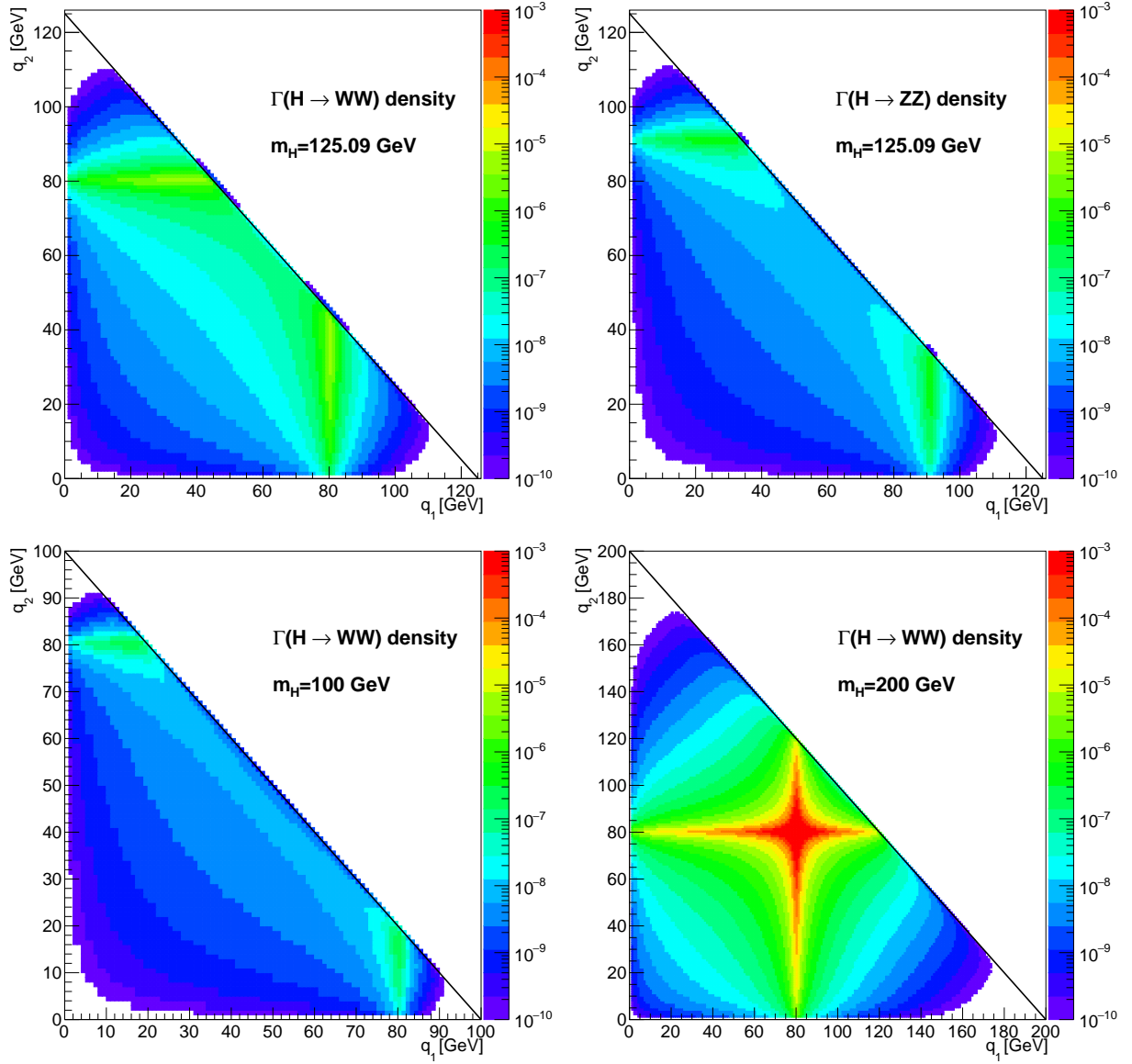


Figure 1: The partial width densities of the Higgs boson into various diboson mass combinations, in GeV per GeV^2 . Top row has WW (left) and ZZ (right) for $m_H = 125.09$, The bottom row shows the WW partial width for $m_H = 100$ GeV and $m_H = 200$ GeV for comparison. The density in this last plot is truncated to keep the scale uniformity.

and ZZ widths have largely cancelled in the ratio. A scale factor of 1.01 is therefore applied to subsequent results for $m_H = 125.09$ GeV. This is reminiscent of the K factor approach to coupling analysis where a leading order framework is used to calculate a scale factor on the complete calculation.

The ratio $\text{BR}^{WW}/\text{BR}^{ZZ}$ as a function of the W width, ignoring the uncertainties on all the

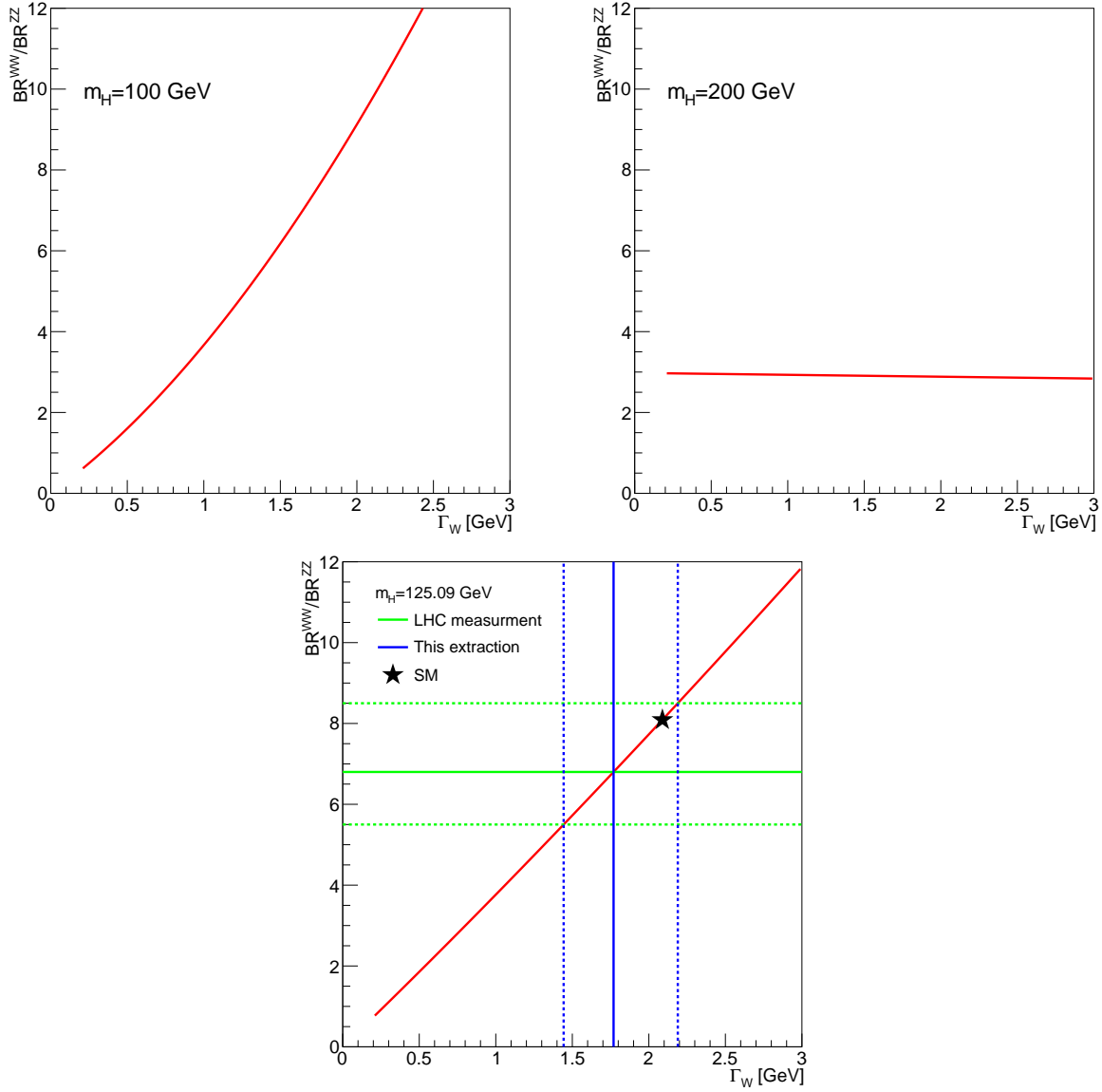


Figure 2: The ratio BR^{WW}/BR^{ZZ} as a function of the W boson width, with all other parameters fixed. It is evaluated for m_H of 100, 200 and 125.09 GeV in the three subfigures. The final figure shows the LHC measurement of the ratio of Higgs boson branching ratios $BR(H \rightarrow WW)/BR(H \rightarrow ZZ)$, in green, the extracted Γ_W in blue, and the SM expectation is in black.

other parameters, is shown in figure 2. Had the Higgs boson decayed to two on-shell bosons the width would scarcely have entered. If both vector bosons had been virtual, as is the case for a SM Higgs boson of 100 GeV, the dependence would have been roughly quadratic. With the actual mass there is one real and one virtual gauge boson and the width is, to a good approximation, proportional to Γ_W . This supports the 1% correction via a scaling of the ratio to the full calculation. The equation is numerically inverted to find the range of widths which

corresponds to the measured branching ratio range. This is:

$$\Gamma_W = 1800_{-300}^{+400} \text{MeV} \quad (3)$$

An alternative presentation would be to invert the assumptions, and say that the 2% uncertainty on Γ_W represents a 2% uncertainty on $\Gamma(H \rightarrow WW)$ which should be allowed for in the analysis.

2.1 Errors from the extraction procedure

The extraction of the ratio of branching ratios from the LHC data currently has limited precision, mostly for statistical reasons, but also with many systematic errors. These are not the subject of this note, which considers that input as a given. Only the errors discussed below affect the interpretation.

The Higgs boson mass of $125.09 \pm 0.21 \pm 0.11$ GeV has the largest mass uncertainty in the formula. It changes the extracted value of Γ_W by around 0.2 MeV, which is clearly negligible, and similarly the W and Z boson masses contribute negligible uncertainty.

The Z boson width is known to 2 per mille, and this translates to a 1 per mille or 2 MeV uncertainty on the prediction of $\Gamma(H \rightarrow ZZ)$. This is far below the precision achievable at LHC and is ignored here.

The width of the Higgs boson could also influence this result by changing the relative suppression of WW and ZZ states. The tightest model-independent upper limit on the H boson width is 3.4 GeV from the CMS studies in the $llll$ final state.[13] An integration over the Higgs boson width has not been made, but its magnitude is estimated by changing the mass by 3.4 GeV, which gives a 3 MeV shift in the extracted Γ_W . This is again negligible.

There is a 1% correction made in the double ratio between the first order calculation used here and the full calculation. However, the measured value is compatible with the SM expectation, and so the calculation has been corrected to the full calculation at least in some part of the range. The total calculational error is expected to be dominated by the uncertainty with which both the WW and ZZ partial widths are calculated, 0.5%[6]. A pessimistic combination of these, 1%, gives the largest uncertainty on Γ_W , 20 MeV.

In summary, the total error of the extraction is estimated to be 20 MeV, which is negligible in comparison with the experimental error.

3 Discussion and outlook

The partial width $\Gamma(H \rightarrow VV)$ is proportional to the full width of the vector boson involved. While it is possible to impose the SM expectation, this seems to this author a restrictive way of testing the SM. The alternative, of using the experimentally measured value, should at least be considered. The 2% uncertainty on $\Gamma(H \rightarrow WW)$ from the limited experimental knowledge of the W boson width is currently well below to 20% uncertainty from the Higgs boson couplings.

The alternative presentation, discussed here, treats the Higgs boson physics as known and the W as unknown and is perhaps extreme, but under this assumption $\Gamma_W = 1800^{+400}_{-300}\text{MeV}$ has been extracted. A conservative 20 MeV error on the W boson width is estimated due to uncertainties on the calculation of the partial widths to WW and ZZ .

The uncertainty on this derivation of Γ_W is thus dominated by the errors on the Higgs boson WW and ZZ measurements and will remain so at HL-LHC. Various projections for these in the future exist. For example, ATLAS concluded [14] that 5% and 4% errors on the $H \rightarrow WW$ and $H \rightarrow ZZ$ signal strength, respectively, were possible using 3000 fb^{-1} if theoretical systematic errors are ignored. Some of these theoretical errors will cancel in the ratio, so an error approaching 7% error might be achievable, and presumably a combination of two experiments will be better. At this point a 2% error on Γ_W would have a significant impact on the physics interpretation.

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